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Improvements to the Sandia CTH Hydro-Code to Support Blast Analysis and Protective Design of Military Vehicles

Presented at the NATO/STO AVT-221 Specialists Meeting on "Design and Protection Technologies for Land and Amphibious NATO Vehicles", Copenhagen, Denmark, Apr 07-10, 2014

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14. ABSTRACT

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15. SUBJECT TERMS

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ABSTRACT

High fidelity simulation of the effects of buried explosive devices on military vehicles requires accurate models of the Equation of State and constitutive properties of the soil and efficient procedures for applying blast loads in finite element structural dynamics codes such as LS-DYNA. The ERDC Hybrid Elastic Plastic (HEP) geo-material model has proven to be an effective model for a wide variety of soils and other geo-materials in Lagrangian finite element simulations of blast and penetration. This paper describes the implementation of the model in the Sandia CTH Eulerian hydro-code and verification of the implementation with experimental results from ERDC Impulse Measurement Device (IMD) tests. In addition, modifications to CTH to automate the extraction of blast pressures for use in LS-DYNA is described along with results from two large scale analyses that were used to validate the coupling procedure.

Keywords: Blast, soil modelling, Eulerian hydro-code,

1.0 INTRODUCTION

Accurate tools and procedures for simulating the blast effects of shallow buried explosive devices are critical to the U. S. Department of Defense and NATO's efforts to design blast-resistant vehicles that can increase crew survivability and counter the threat from improvised explosive devices. Of the available tools for blast simulation, the CTH (CHART Squared to the Three-Halves) Eulerian shock physics code from Sandia National Laboratories [1] is one of the more popular and is commonly used throughout the DoD complex for standard air blast simulations. However, some limitations in CTH's capabilities for under-body blast simulations have been noted. Researchers at MSU-CAVS, TARDEC, and ERDC identified two areas of improvement to CTH that would enhance its value as an analysis tool for under-body blast analysis and protective design simulations. In particular, the two areas of improvements to CTH that were of most value to TARDEC and ERDC were implementation of better material models for soils to support buried mine simulation and procedures for utilizing CTH generated blast loads in LS-DYNA structural dynamics simulations. This paper will describe research conducted at Mississippi State University's Center for Advanced Vehicular Systems to implement these improvements and to apply them to realistic underbody blast scenarios.

2.0 HEP GEO-MATERIAL MODEL CTH IMPLEMENTATION

Although a wide array of material models are implemented in CTH, it does not support the U.S. Army Engineer Research and Development Center (ERDC) Hybrid Elastic-Plastic (HEP) geo-material model [2,3] that has proven to provide accurate simulations of the response of a variety of geo-materials subjected to large-deformation, high strain rate behaviour. The HEP model was originally developed under ERDC funding to model ground shock. The model was extended over the years and applied to a variety of blast and penetration problems. ERDC has fit the model to a wide variety of geological materials ranging from soils to conventional strength concretes and rocks. The HEP model has been validated against explosive field tests for a variety of materials. ERDC maintains a library of materials fit to different model variants. The majority of the materials in the library have been fit to the Simple (SHEP) model variant. To date, the model has been implemented in Lagrangian finite element codes such as SABER, EPIC, and PRONTO3D. To the best of our knowledge, the work described in this paper was the first successful implementation of the model in a production Eulerian code.

In this research, the simple HEP (SHEP) model [3] was implemented in CTH Version 9.1 and subjected to a variety of verification and validation tests that compared results with experimental data and other simulation tools such as EPIC. A complete description of the model implementation along with a description of the changes to existing CTH routines is given in Reference 4. An initial set of verification tests were performed on the simple witness plate geometries used by Kerley [5, 6, 7] and Littlefield [8]. The results of these tests revealed the model performed well when compared to results using Kerley's soil model and the EPIC implementation of the HEP model. A more realistic series of tests were performed using results from experiments conducted using the ERDC Impulse Measurement Device (IMD) as well as results from EPIC simulations [9, 10].

2.1 Overview of the ERDC IMD tests and Bessette's CTH model

The ERDC IMD facility shown in Figure 1 was designed and built by ERDC under joint TARDEC and USACE funding to obtain data on the above ground environment created by the detonation of shallow-buried explosives. The facility was designed to obtain data on overpressure, impulse, and ground shock for different soil types. A complete description of the IMD facility, the testing procedures and instrumentation, and the test conducted with the facility is given in Reference 9. ERDC developed three test soils for the initial IMD experiments that were representative of a wet clay material, an intermediate soil, and a dry sand. The IMD experiments included above ground, partially buried (surface tangent), and shallow buried detonations in the three test soils. Other data such as side-on pressure and ground shock data were also obtained. The distance of the plates to the top of the charge was maintained at 20 inches for all the test configurations. The explosive charge for all tests consisted of a 5lbm (2,268 kg) cylinder of C4. The depth of burial (DOB) for the shallow buried tests was fixed at 4 inches.

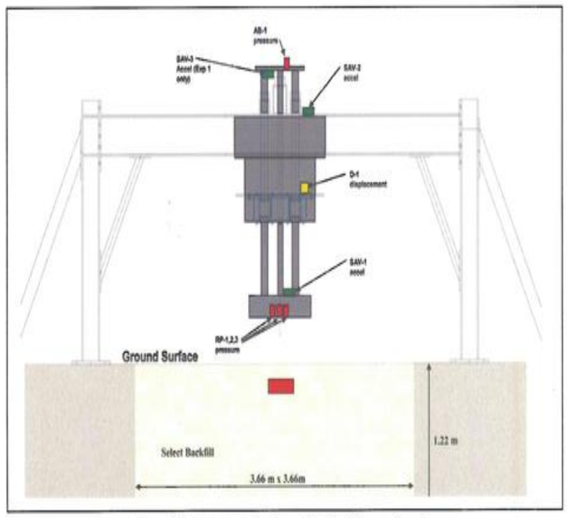


Figure 1: ERDC Impulse Measurement Device experiment (Reference 9)

Initial tests of the HEP model by the first author using the IMD experimental data only modelled the target plate with the dimensions of the plate modified to match the total mass of IMD plate and piston assembly. Bessette et al. (2012) (Reference 16) developed a more detailed model of the IMD geometry and examined the effect of variables such as mesh spacing and a reactive burn detonation model on the HEP model results. A CTH material plot of the initial configuration used in this modelling is shown in Figure 2. The piston-plate assembly is shown in grey. The darker brown material is the test bed soil (a wet clay material for this analysis). The lighter brown material is the *in situ* soil that is modelled as a silty clay material using a P-alpha model. The C4 charge shown in red was modelled using the Sandia History Variable Reactive Burn model (HVRB). The small spot of green material is a PETN booster charge that is used to initiate the detonation process for the HVRB model and is modelled using the Jones-Wilkens-Lee (JWL) Equation of State (EOS). The surrounding air is removed from this plot for clarity. A very fine 2D cylindrical mesh (2mm cell size) is used in the areas around the explosive, test bed soil, and IMD structure.

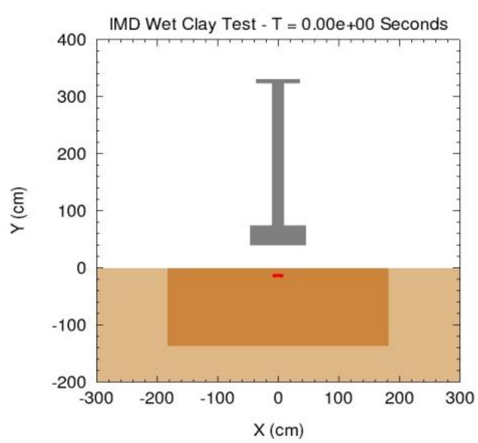


Figure 2: More Detailed CTH model of IMD experiment (Reference 16)

The IMD shallow-buried explosion test for the IMD wet clay material was run by the first author using the more detailed CTH model from Reference 16. Results for impulse and material response of the soil generated by the CTH HEP model were compared with results obtained using the Reference 16 fit for the IMD wet clay. The total number of computational cells used in the simulation totalled over 7 million. The extent of the soil materials was taken to be semi-infinite. All runs were made using 192 cores on the MSU Talon cluster. Figure 3 compares the impulse up to a time of 15 milliseconds generated by both the CTH HEP and the P-alpha model fit from Reference 16 with the peak impulse reported by Ehrgott [9]. Both models are seen to provide excellent correlation with the experiment. Figures 4a-4d show the material response for both models at t=5.e-4, and 15e-3 seconds. The 5e-4 second results show the size and shape of the plug of soil uplifted by the explosion just prior to impacting the target plate. The impact of the soil plug with the plate accounts for a significant part of the total impulse delivered to the plate for a shallow buried explosion. Therefore, accurate prediction of the momentum of the soil impacting the plate is an important part of any shallow buried explosion simulation. A close examination of these results shows a slight loss of material at the top of the soil plug for the Reference 16 fit. This loss is most likely due to the effects of the material discards used in the problem. The late time material plots illustrate the crater geometry predicted by both models. In general, both models predict crater depths close to the experimental results. However, care must be taken when trying to interpret information on crater growth from CTH material plots. For multi-material simulations, CTH will frequently encounter small bits of material exhibiting non-physical temperatures or pressures that lead to very small time steps or the simulation “blowing up” due to negative temperatures. The only cure for this non-physical behaviour is to explicitly discard the materials from the simulation. However, this can lead to strange behaviours in the material plots particularly at late simulation times. One interesting aspect of these runs was the dramatic difference in run times required for each simulation. As seen in previous tests, the CTH HEP implementation was dramatically more stable requiring 83,311 cycles and 30,320 CPU seconds to reach completion compared to the Reference 16 fit which required 229,492 cycles and 82,090 CPU seconds.

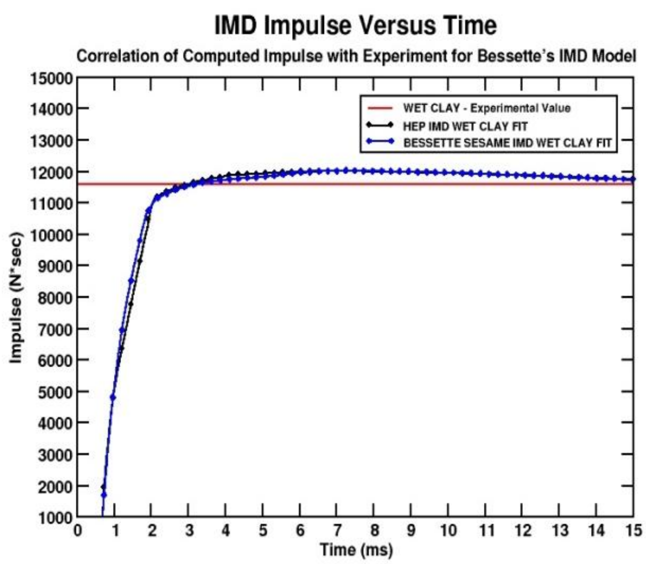
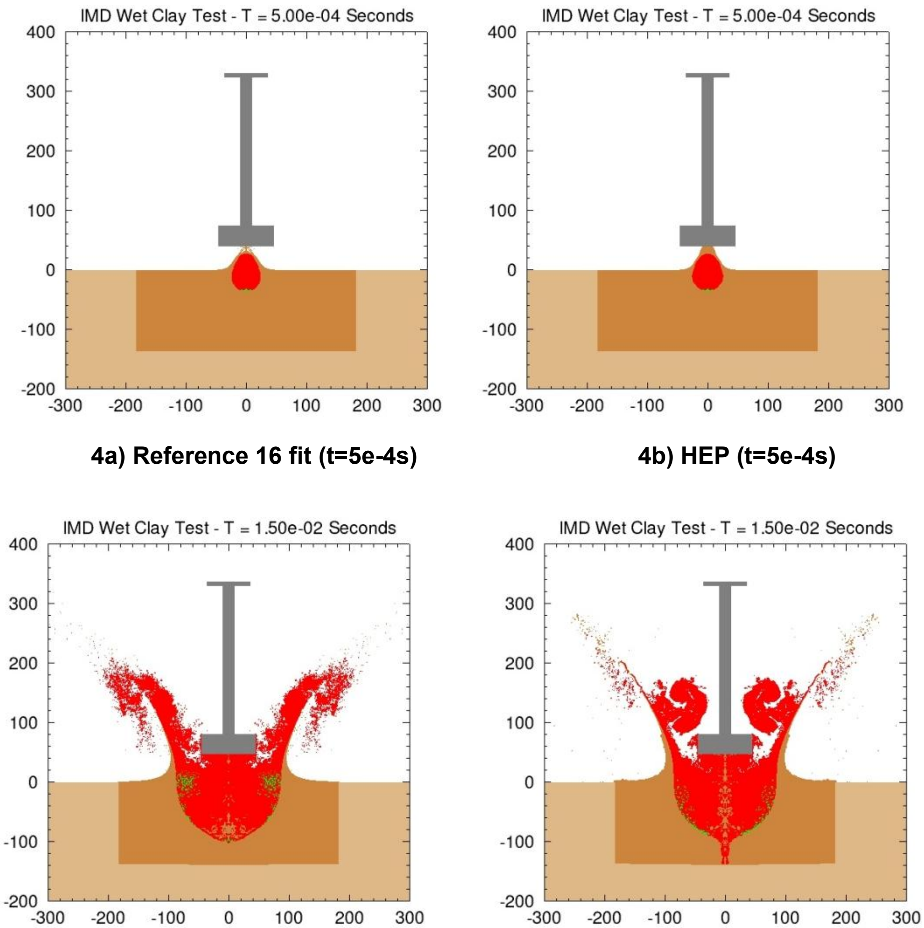


Figure 3: Comparison of computed IMD impulse with experiment for HEP and Reference 16 fit



4a) Reference 16 fit (t=5e-4s) **4b) HEP (t=5e-4s)**

4c) Reference 16 fit (t=15e-3s) **4d) HEP (t=15e-3s)**

Figure 4: Comparison of CTH material plots for Reference 16 fit and HEP at two times

To support the development of the MineX3D tool described in the next section, Bessette re-ran his detailed model for all three IMD test soils using the HEP model. His results for the wet clay material matched the results obtained by the first author. Figure 5 compares the Bessette's values of the computed impulse for the intermediate soil and the dry sand materials with experimental results obtained by Ehrgott in the initial 2010 tests [9]. The computed impulse for the intermediate soil is seen to correlate well with the experimental value. The overshoot in the peak value is a result of using the HVRB reactive burn model. The dry sand material is seen to under-predict the impulse when compared to Ehrgott's 2010 results. However, a second series of tests using the dry sand material performed in 2012 [12] yielded peak impulse values that were much closer to the CTH HEP results. ERDC performed an additional test in 2012 to determine the repeatability of the lower impulse value for the dry sand that again yielded a lower value than the 2010 test. The cause of this discrepancy is still being investigated. However, the correlations with the 2012 results reported by Bessette show excellent agreement for all three test materials. As a result of the success of the IMD test simulations, Dr. Bessette has made extensive use of the CTH HEP model in the development of the MineX3D fast running engineering level analysis tool described in the following section.

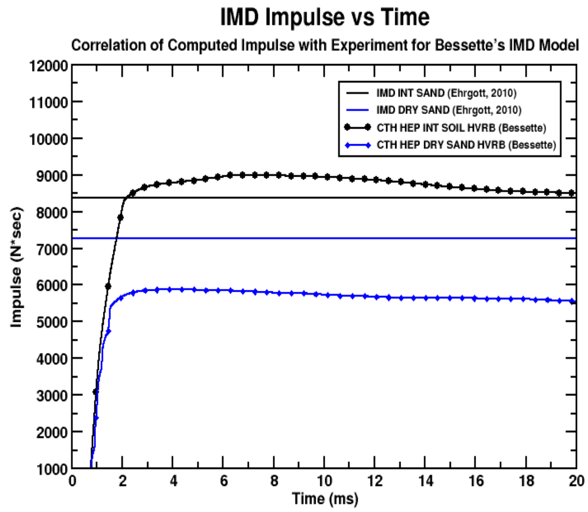


Figure 5: CTH HEP IMD Intermediate Soil and Dry Sand impulse

2.2 MineX3D overview

The MineX3D code [11] is an engineering-level model designed to predict the loading environment on the underbelly of a vehicle from a close-in detonation of an explosive charge placed on or within the underlying soil. The code relies on independently generated tabular source models (TSM) that describe the conditions arising from an explosion on or within an arbitrary soil type without a structure overhead. The TSM tracks the time-dependent state of freely expanding materials (air shock, soil, and HE products) at various fixed points overhead. MineX3D retrieves the state data from the TSM, and then transforms the data to account for any obstacles (e.g., a vehicle) that are in the flow field. The code takes into account the combined air, soil, and HE product interaction on the structure, and applies any enhancement factors for the interface pressure in order to account for the dynamic structure interaction.

The TSM database plays a key role in the load prediction. All TSM development to date has been conducted using the MSU-CAVS version of CTH, with the HEP model handling the soil response. The HEP model underwent a rigorous evaluation using data from the IMD test series [9, 11, 12]. The model was found to perform well over a wide range of experimental conditions, including variations in soil type, depth of burial, and clearance distance between the IMD and ground surface. The early validation effort provided confidence in the HEP model and its subsequent application for TSM development.

3.0 ONE-WAY CTH TO LS-DYNA COUPLING PROCEDURE

The second improvement made to CTH in this research was the implementation of a simplified procedure for generating LS-DYNA load curves from blast loads computed by CTH automatically using standard LS-DYNA input file information to define the geometry and the target surfaces to be loaded by the blast pressures. The steps in the coupling procedure begin with development of the initial parts of the LS-DYNA model input that define the nodes and elements of the surfaces to be loaded by the CTH pressures and a stereo lithography (STL) format geometry file of the finite element model exported by the LS-DYNA pre and post processor, LS-PREPOST. This input data is read by logic implemented in CTH and used to define the CTH cells that will contain the pressures needed to generate LS-DYNA load curves. The LS-DYNA geometry is modelled in CTH as a rigid material. A CTH run is then made in which either instantaneous or time averaged values of cell pressures are extracted at user defined time intervals and stored as time histories that are used to generate output files in text format that can be cut and pasted directly into the final LS-DYNA input files. Finally, LS-DYNA is run using the CTH generated pressures to load the target surfaces. This represents a form of "one-way" coupling between CTH and LS-DYNA that is suitable for many preliminary design tasks. The coupler was validated by comparison with results from the DRDC-Valcartier plate experiments [13] reported in the 7th International LS-DYNA Users Conference. A second large-scale simulation was run using the TARDEC Generic Hull notional vehicle geometry [14] to demonstrate the ability of the procedure to generate realistic results for a large scale military vehicle analysis. The results of these two simulations are described in the following sections.

3.1 Simulation of the DRDC plate experiment

The DRDC plate experiment was used to validate the coupling procedure for a large-scale simulation. TARDEC supplied MSU-CAVS with LS-DYNA input decks that modelled the DRDC experiment using both the CONWEP blast load model in LS-DYNA along with LS-DYNA ALE simulations. These input decks were run at MSU using both the ALE and CONWEP inputs. The results of these runs are described in detail in Reference 4. Summarizing the results of described in Reference 4, the LS-DYNA CONWEP runs showed deflections in the target plate geometry that were consistent with the experiment but the ALE simulations resulted in the target plate fracturing under the blast load. Several numerical experiments were conducted to determine the cause of the fracture. These experiments indicated that the parameters used in the Johnson-Cook fracture model were resulting in premature failure of the plate. As a result of a second series of numerical experiments, the fracture model parameters were modified to set the leading value (D1) to 150% and the rest of the parameters to zero. The effect of this modification is to turn off all rate and thermal effects in the fracture model. Although there is no physical basis for this modification, the premature fracture seen with the default inputs was eliminated and the results were consistent with the experiment. The modified values of the fracture model input were used in all subsequent simulations. An initial set of CTH alone simulations were run to determine the effect of various parameters such as mesh spacing on the simulation results and to define the final CTH inputs used in the coupler tests.

3.1.1 Description of the CTH model inputs for the DRDC plate experiment tests

For the CTH DRDC plate simulations, the soil was modelled using the CTH HEP model for the IMD dry sand material. The dry sand material density does not match the density of the soil used in the LS-DYNA simulations but was chosen based on the results from the ERDC IMD experiment simulations and represents a lower bound on impulse that will be applied by the soil and explosion to the target plate. The target plate used was the 5083 aluminium plate used in the LS-DYNA inputs MSU-CAVS received from TARDEC. The plate thickness used was the experimental value of 3.175 cm. As reported in Reference 13, the explosive charge consisted of a 6 kg cylinder of C4 with a diameter of 25.4 cm and a thickness of 7.62 cm. The DOB is taken to be to the top of the charge and was set at 5 cm. The default Johnson-Cook constitutive model for 5083 aluminium was used with the individual parameters adjusted to match the LS-DYNA input values. The Johnson-Cook fracture model was also used. The SESEME Equation of State values for 2024 aluminium with density adjusted to match the 5083 value was used for the target plate due to the lack of a default EOS model for 5083 aluminium in CTH. The steel support frame was modelled using the SESAME EOS tables for 4340 steel for the EOS input and the default Johnson-Cook steel values in CTH were used for the constitutive model. The surrounding air was modelled using the SESAME EOS. Quarter symmetry was used to reduce the problem size. However, the thin plates used in the geometry require a fine mesh to resolve the material. Therefore, a graded mesh using 5 mm mesh spacing in the immediate region of the test geometry and the charge was used with mesh stretching used to extend the mesh to appropriate outer boundaries. Even with a mesh grading, the resulting mesh contains 280x280x480 (37,632,000) cells. Due to the size of the grid, these simulations were run on the MSU HPCC Talon cluster using 192 cores. The LS-DYNA model of the DRDC experimental geometry is shown in Figure 6. A 3D view of the initial CTH configuration is shown in Figure 7. An additional 10 metric tons of weight that sits on top of the reaction frame was also modelled but is not shown.

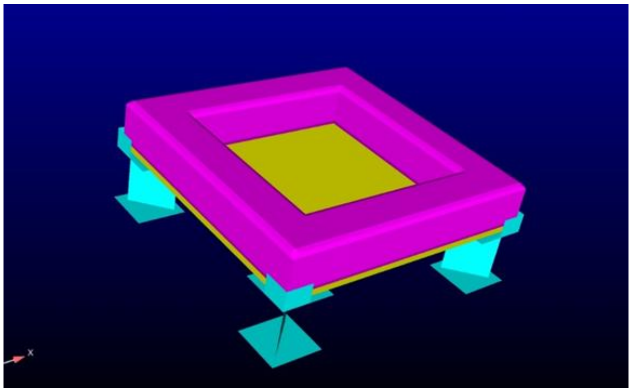


Figure 6: TARDEC LS-DYNA model of DRDC plate experiment

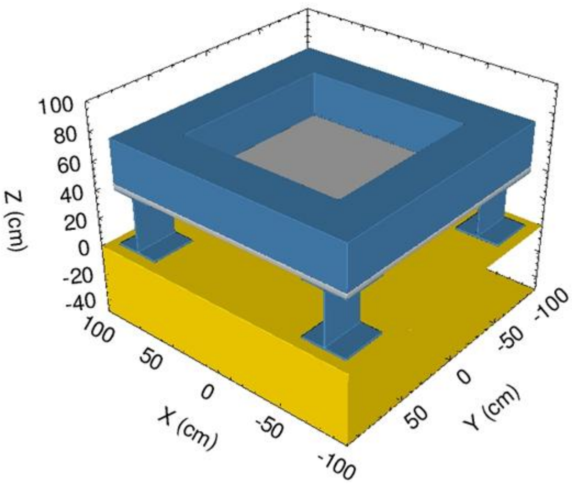


Figure 7: Initial CTH material configuration for DRDC plate model

Two sets of simulations of the DRDC plate experiment were performed using the CTH/LS-DYNA coupler. In the first set of simulations, the instantaneous pressures on the plate were used to define the load curves. In the second set of simulations, a time averaged pressure approach for defining the load curve pressures was used. This time averaged pressure approach is used by Sandia for coupling CTH with the Sandia PRESTO finite element code and is also used in the CTH rigid material model. The CTH inputs for the DRDC geometry developed for the CTH alone calculations were used with the exception that the supporting legs were removed to match the definition of the load curves generated by LS-PREPOST. The 5 mm mesh spacing used in the CTH alone case was repeated in the coupled cases. CTH simulations were first run to 5e-3 seconds and the extracted load curves were fed into an LS-DYNA simulation that ran to 8e-3 seconds. Figure 8 compares the displacement of the plate at element locations in the symmetry plane of the plate from the plate center-line to the plate edge computed using both the instantaneous and time averaged CTH pressures with experiment. It is seen that the time average results gives a much better correlation with experiment for this case. The over-prediction of the deformation near the plate edge with the time-averaged pressures needs to be investigated further. A contour plot of target plate displacement is shown in Figure 9. These results illustrate that the coupling procedure can provide reasonably accurate results for large-scale structural dynamics simulations of the response of a structure to shallow buried explosion loads.

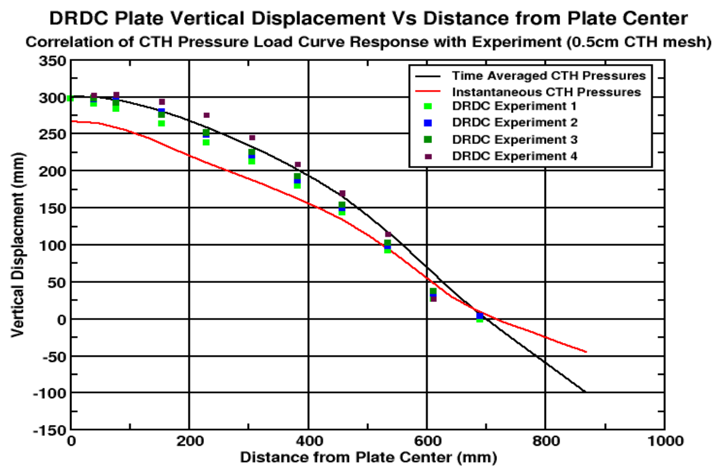


Figure 8: Comparison of computed plate deflections with experiment

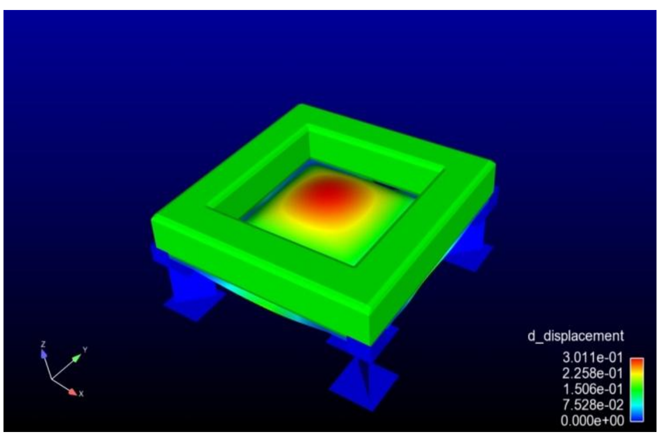


Figure 9: Displacement contours using time-averaged CTH pressures

3.2 Simulation of Generic Hull experiment

The TARDEC Generic Hull experiment [14] was designed to provide a notional geometry for underbody blast analysis and to evaluate blast mitigation technologies. Historically, the Department of Army has had difficulty collaborating with industry and academia on underbody blast events due to the sensitive nature of the work. Data generated from testing military vehicles is typically rated CLASSIFIED and not readily sharable. To alleviate this issue, TARDEC has fabricated a generic vehicle hull shown in Figure 10 with the intent to share data with academia and the industry to spur innovation in blast mitigation technologies. As a first step in the simulation process, an STL file of the exterior of the GHULL LS-DYNA model was generated using LS-PREPOST. Figure 11 shows that all the details of the external geometry of the LS-DYNA model are preserved in the STL file. Next, a set of elements that define a LS-DYNA LOAD_SEGMENT input were specified for the under-surface of the GHULL configuration. The parts of the under-surface that are loaded by CTH pressures are shown in white in Figure 11. Due to the number of elements in the LS-DYNA model, this procedure resulted in 46,729 LOAD_SEGMENT entries. This represents an extreme test of the one-way coupling software. A CTH run was created that contained approximately 149 million cells (900x360x460 cells). The mesh spacing is a constant 1cm in all three axes. The soil was modelled using the HEP IMD intermediate soil material fit which is an intermediate silty sand with a wet density of 2.01 g/cm^3. An explosive charge consisting of a 6 kg charge of C4 was placed at a DOB of 2 inches. These values are consistent with the NATO STANAG 4569 Level 2 mine threat. CTH simulations were run out to 2e-3 seconds and the load curves generated where included in an LS-DYNA simulation of the complete vehicle that ran out to 5e-3 seconds. For the CTH simulations, half-symmetry was employed but the full geometry was used in the LS-DYNA runs. This tested a feature of the one-way coupler that allows users to input a full LS-DYNA geometry into CTH but assume half or quarter symmetry in the CTH simulation. Results from the simulation are given in Figures 12 to 15. Figure 12 shows the displacement of the external shell at 5e-3 seconds. Figure 13 shows the external pressures remaining on the underside of the vehicle at 5e-3 seconds. Figures 14 and 15 show the effective stress and displacement of the internal frame and false floor at 1e-3 and 5e-3 seconds. These results are similar to those obtained by the MSU Loci-BLAST code with a two-way coupling to LS-DYNA [15]. The success of this simulation demonstrates that the one-way coupler can handle complex geometries and provide acceptable accuracy for predicting the effects of buried mines on realistic military vehicle geometries.

Figure 10: TARDEC Generic Hull test geometry

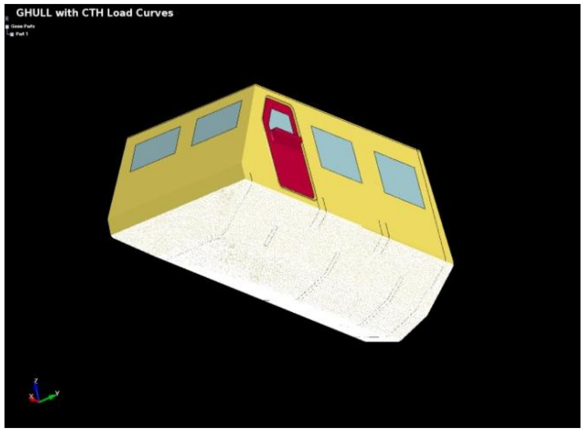


Figure 11: LS-DYNA STL geometry (loaded surfaces shown in white)

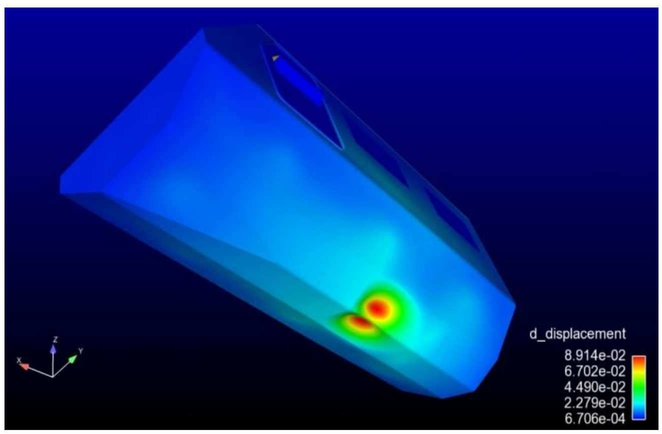


Figure 12: Contours of external hull displacement at t=5e-3 second

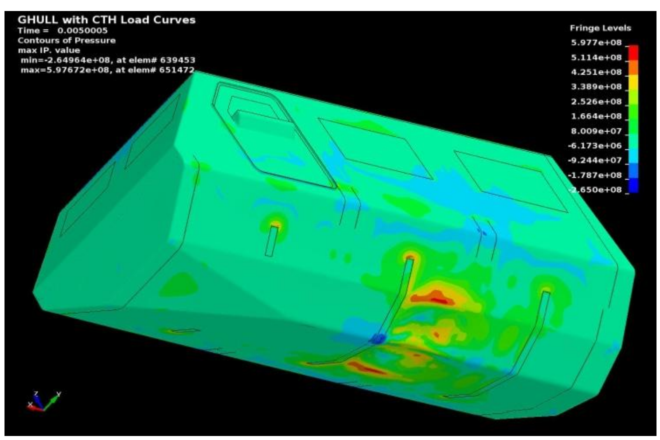


Figure 13: Contours of external hull pressure at t=5e-3 seconds

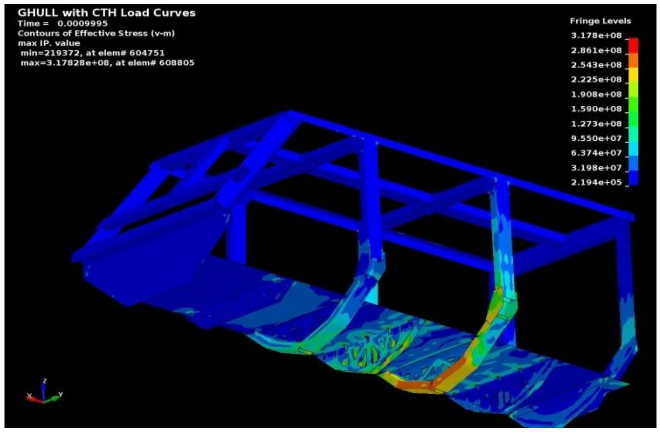


Figure 14: Contours of effective stress on the internal frame at t=1e-3 seconds

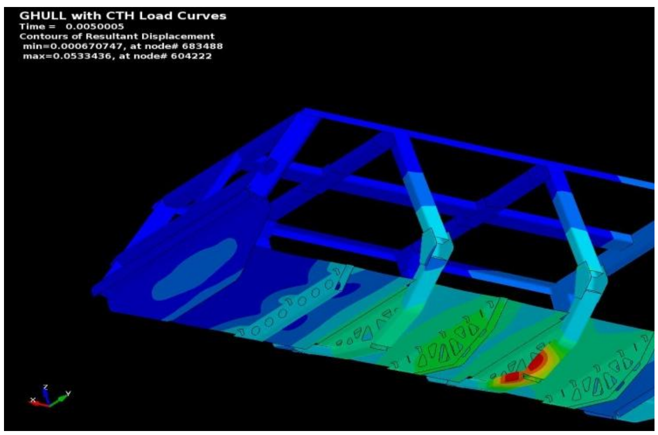


Figure 15: Contours of displacement on the internal frame at t=5e-3 seconds

4.0 SUMMARY AND CONCLUSIONS

Two improvements to the Sandia CTH Eulerian code that enhance its effectiveness as a tool to support military vehicle blast analysis and protective design were defined and implemented in CTH V9.1. The first improvement was the incorporation of the ERDC Hybrid Elastic-Plastic (HEP) geo-material model to support simulation of shallow buried explosions in a variety of soil types. The model was validated a variety of experimental results including the ERDC IMD experiments. The CTH HEP implementation was shown to provide excellent correlation with IMD impulse results for the three IMD test soils. The second improvement was the implementation of a procedure for automatically extracting blast pressures from a CTH calculation to use as load curves in an LS-DYNA structural dynamics simulation. This “one-way” coupling procedure was applied to compute the structural response of two large-scale geometries, the DRDC plate geometry and the TARDEC Generic Hull notional vehicle geometry. Both simulations demonstrated the viability of the coupling procedure for computing the structural response of vehicle under-bodies to shallow-buried explosions. These two improvements were shown to enhance the usefulness of CTH as a tool for military blast analysis and protective design.

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